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SWITCHING IN AIRCRAFT ELECTRICAL NETWORKS

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ABSTRACT

Electrical power in aircraft is different from any existing system. It is an isolated network in a very rough environment. Standard generators supply 120V at 400 Hz, but new concepts also use wild frequency solutions from 380 to 1000 Hz. The temperature range for components is -55°C to +125°C. Combined with an air pressure varying from 10^3 to 50 hPa and multiple dewing and drying cycles under normal operation conditions this environment requires innovative solutions, especially taking into account that light weight is a major property of all airborne equipment.

In modern airliners several hundreds of kilometers of cables are installed and the protection against overload and short circuit is a major concern to avoid fire on board. Switching loads under all these severe conditions therefore is the challenge for aircraft circuit breakers. Technical and physical particularities of switching at high frequency and low pressure are discussed.

Low energy arc faults are able to ignite cable insulation and surrounding material. Therefore arc fault detection devices had been developed, which use complicated algorithms to differ fault signals from normal load signals. The technology is available and intended to be used in future load management systems.

Future electronic solutions for switching problems may not depend on pressure and frequency, but regarding size and power dissipation at alternative current they can still not compete with mechanical contacts.

Index Terms – aircraft circuit breaker, aircraft power generation, variable frequency, low pressure, arc fault, fault interruption, 400 Hz, 800 Hz, 1000 Hz

1. ENVIRONMENT

A large part of the switching devices used in aircraft electrical networks is mounted in areas without air conditioning and without pressure compensation. As aircraft circuit breakers are generally not enclosed and use the surrounding air as insulating gas, the thermophysical properties of the atmosphere have to be considered regarding the switching operations of such devices. The earth's atmosphere is subdivided into the troposphere up to about 15 km altitude, the stratosphere up to about 50 km altitude, the mesosphere up to about 80 km, the thermosphere up to about 640 km altitude and the exosphere up to about 100,000 km altitude which is passing smoothly into the interplanetary space. Civil planes hardly fly higher than 10 to 12 km. Manned military missiles reach altitudes of up to 35 km. Unmanned military missiles or spacecraft reach altitudes of up to 200 km or even the orbit. Temperature as a function of altitude in general shows a very non-linear shape, even the gradient changes sign several times. The temperature range required for aircraft components therefore covers -55 °C to +125 °C.

The air pressure decreases with increasing altitude and may be obtained e.g. by the *International Barometric Formula*, which is valid up to 12,000 m. For altitudes above 12 km tabular values may be used. For 10,000 m e.g. the remaining pressure is 265 hP. The moisture content of air may be disregarded for switching operations below 1000 V [1].

2. GENERAL DESIGN OF AIRCRAFT ELECTRICAL NETWORKS

The energy demand of passenger planes rose remarkably in the last 50 years (figure 1). More convenience in the passenger area and the increased replacement of hydraulic actuators by electromagnetic ones in the last years are regarded as the main reasons for this increase. The installed generator capacity of passenger planes has almost decupled since 1954. Especially in the last ten years, a strong increase in energy demand could be noticed. The power provided in modern passenger planes is meanwhile exceeding the 1 MW limit. In order to augment the load capability of the iron and copper sections, an aircraft frequency of 400 Hz is used. As a result, a high generator power is achieved while dimensions and weight are low. These are decisive factors in aircraft construction. The limits of a raise in frequency result from an increased reactive power and higher magnetization losses in the iron parts. The latest technology of generating energy in aircraft electrical networks uses generators which do not need hydromechanical transformers. Therefore, the frequency used in aircraft networks varies from 380 to 800 Hz. These nets are also called "variable frequency nets" or "wild frequency nets". Such a concept has been completely realized for the first time in the new airbus A380. The newly planned Boeing 787 will also use a variable frequency net [3]. This requires a testing of existing aircraft circuit breakers in this frequency range and, if necessary, taking measures to handle these changed conditions.

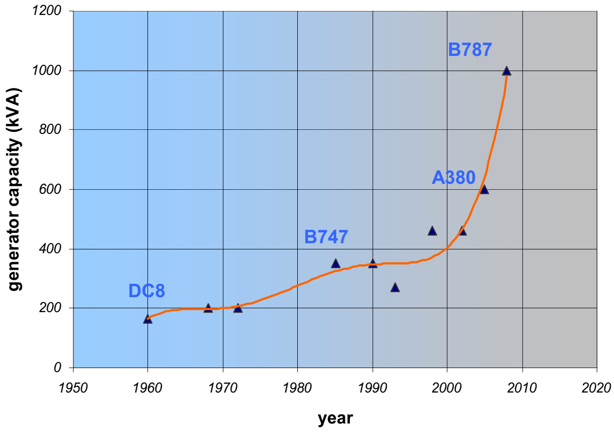


Figure 1 Installed electrical generator capacity in passenger aircraft since 1960

The generators in general are driven by the turbines. In aircraft a high safety level is required which results in demanding high system redundancy. Besides the main generators there is an auxiliary power unit (APU) normally providing a capacity marginally above the one of a main generator. Additionally there is an emergency battery feeding into a 28 V DC net, which is coupled via converter to the AC side. A third backup system so to say a ”last spare tire” is a so called ram air turbine (RAT), which works only above a speed of 200 km/h. In case of emergency a propeller coupled to a small generator swings out of the fuselage into the air stream thus providing a small amount of electrical energy even with engines off.

In today’s aircraft electrical networks the main distributions are separated, i.e. all four generators feed into their own busbar (figure 2), which is electrically not connected with the remaining three busbars. This is not the case in older types of aircraft, where all busbars may be connected in parallel via so called bus tie contactors (BTC). All generators feeding into one main busbar are more critical because of very high currents in case of short circuit and because of more complex electronic systems for generator control.

Almost 50 % of the electrical energy consumed in a modern passenger aircraft is needed for the galleys. In our example (figure 2) these are 150 kVA. The rest is mainly distributed to air condition (12 %), to illumination and hydraulic pumps (15 %).

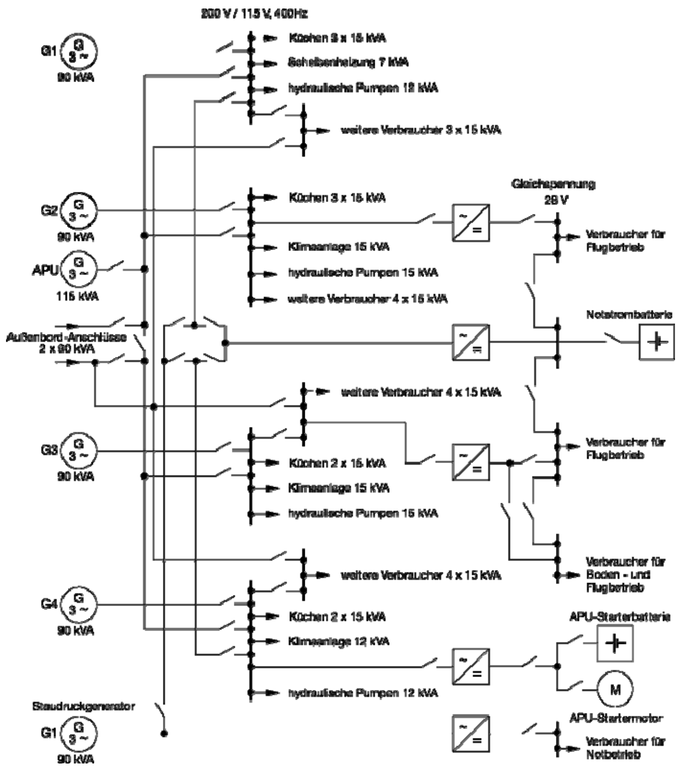


Figure 2 Typical design of an aircraft electrical network [2, p. 66]

3. POWER GENERATION AND DISTRIBUTION

For constant frequency systems at 400 Hz normally separately excited synchronous machines with drum-type rotor, brushless exciter and oil cooling are used. Two pole and four pole machines are common. Therefore taking into account the frequency of 400 Hz a generator rotational speed of n = 12000 rpm for two pole machines can be calculated and n = 24000 rpm for four pole machines respectively.

$$f = \frac{p \cdot n}{60} \qquad (1)$$

f = frequency, p = number of poles, n = rotational speed in rpm

Synchronous machines have to be driven with constant rotational speed. For this reason a hydraulic converter is installed between the turbine shaft and the generator shaft. This so called CSD (constant speed drive) converts a variable turbine speed hydro mechanically into a constant generator input speed. In figure 3 such a system is depicted. It shows GCU (generator control unit), APU, current transformers and integrated drive generator (IDG). The latter means generator and CSD are one unit. A system like this is installed four times in a BOEING B747. The generator capacity is 90 kVA, the input speed may vary between 4500 and 9000 rpm. The hydro-mechanical converter integrated into the IDG delivers a constant generator speed of 12000 rpm. The total weight of such a system is only 63 kg.

Figure 3 Generator system installed in BOEING B747 for one engine; controls, APU, current transformers, generator with CSD (from left to right); overall weight 63 kg

4. OVERLOAD AND SHORT CIRCUIT PRITECTION

Modern passenger airplanes contain more than 300 km of electrical cable. To protect this complex network of wires squeezed into narrow spaces between outer fuselage metal wall and interior plastic covers different protection elements had been developed. For the main busbars providing rated currents over 300 A current sensors plus electronic data processing to control the contactors are used. These components are used for protection as well as for switching ON and OFF. For the downward busbars thermal circuit breakers are used with rated currents between 3 and 150 A. Such devices combine in a very compact volume high short circuit capacity of 2500 A and high resistance to extreme environment conditions like heat, coldness, shock, EMI. For the lower ratings from 3 to about 15 A more and more electronic protection components are favoured. In the following only the features of thermal circuit breaker are contemplated. Figure 4 shows the trip time curve of a thermal aircraft circuit breaker at 23 °C including the limits for -55 °C and 125 °C. The diagram also shows the characteristic curve of a cable corresponding to the rating of the circuit breaker. This limiting curve indicates the time the cable reaches 240 °C when loaded with the associated current. Such temperatures are regarded to be quite usual as rated temperature under normal load conditions in aircraft electrical networks.

Like all safety relevant components for aircraft application also circuit breakers provide redundant failure behaviour. A built-in fail safe function prevents in case of blocked circuit breaker mechanism the wires from overheating and burning. A weak spot is designed into the current path operating as a fuse in case of blocked mechanism and thus safely separating the fault location from the rest of the affected cable loom. After a fail safe tripping event the circuit breaker has to be changed like a fuse. To provide a perfect protection and no tripping as long as the circuit breaker operates normally the fail safe characteristic curve has to be placed between the curves of circuit breaker and cable (see figure 4).

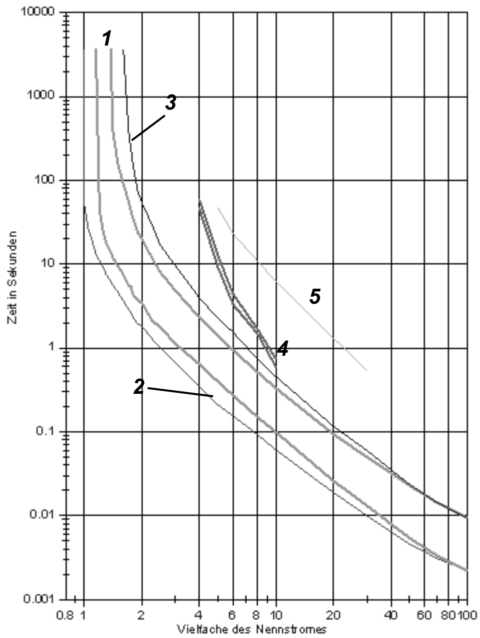
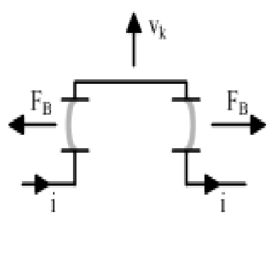


*Figure 4 Trip time curve of standard thermal aircraft circuit breakers; **1** at 2 3°C, **2** at +125 °C, **3** -55 °C, **4** fail safe element, **5** 240 °C limit curve cable*

Thermal aircraft circuit breakers normally consist of a contact bridge system (two points of contact), a latching mechanism, and a bimetal for overload tripping mechanically linked to a second compensation bimetal, which is only influenced by the ambient temperature. In the following the behaviour of such components at higher frequencies is described. For the limited space available in aircraft circuit breakers additional arc distinguishing means usually are left out, i.e. the devices operate as zero-current interrupter. Unlike current limiting breakers in case of overload or short circuit the arc distinguishes the earliest at the next natural current zero crossing. With double contact systems two arcs are generated during opening thus providing higher arc voltages and the conditions for arc extinction may be reached faster. Two different types of breakers had been investigated with two different contact dynamics (figure 5).



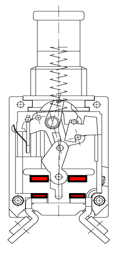


Fig. 5a Transverse contact travel – type 1

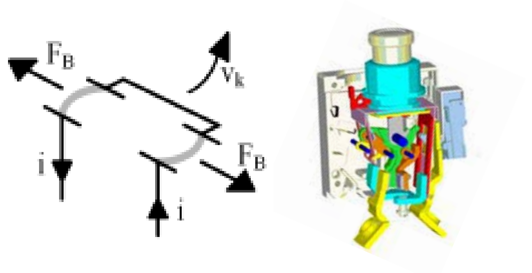


Fig. 5b Rotational contact travel – type 2

Figure 5 Investigated contact systems, i current through contacts, F_B electrodynamic forces on arc, v_k opening velocity of contact bridge

5. INTERRUPTING FAULT CURRENTS IN AIRBORNE ENVIRONMENT

Figure 6 shows an oscillogram of an interruption performed with a breaker type 2 at 100 A_{RMS}, 1000 Hz. The two step changes in the arc voltage signal clearly indicate the opening of the two contact points in rapid succession. The arc extinguishes exactly at the moment when the arc voltage equals to the source voltage. This happens a little bit before the natural current zero crossing, i.e. even in this case a current limiting switching occurs in a certain extent.

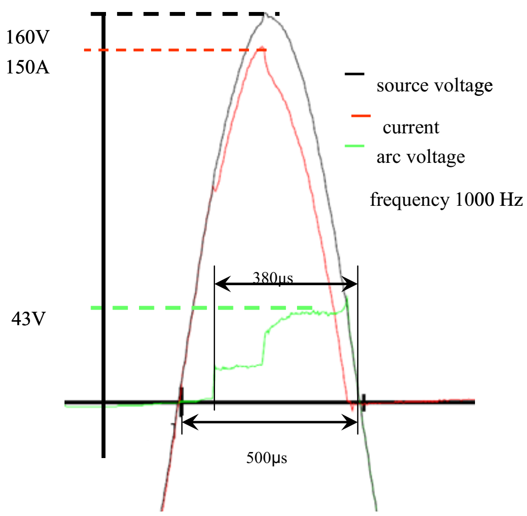


Figure 6 Interruption of 100 A_{RMS} corresponding to 10 x rated current with a circuit breaker type 2 at a frequency of 1000 Hz. The total clearing time is only 480 µs, which is amazing fast for an electromechanical device.

For future aircraft networks it is important to know, weather there is a dependency of frequency in switching behaviour or not. Figure 7 shows a statistical evaluation of overload trip times at 10 i_R and different frequencies for a type 2 breaker. There is a small tendency for trip times to become more slowly with rising frequency. Nevertheless for overload trip times at 10 times and 35 times rated current there could not be found any significant difference within the investigated range between 400Hz and 1000Hz. This result is valid for both types of breakers.

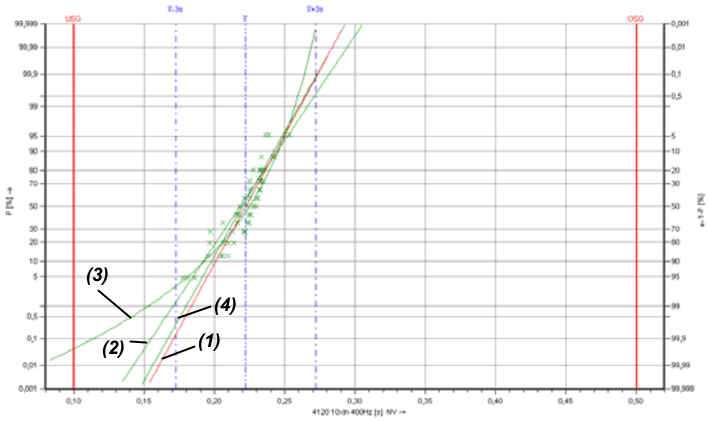


*Figure 7 Statistical evaluation of trip times, circuit breaker type 2, 10 x rated current (100 A), Uq=115V, **(1)** 400 Hz, **(2)** 600 Hz, **(3)** 800 Hz, **(4)** 1000 Hz [3]*

For short circuit interruption the higher rate of rise of the transient recovery voltage $\frac{dU_{TRV}}{dt}$ influences the conditions for arc extinguishing. In spite of the existence of much more current zero crossings the short circuit capacity is degressive with rising frequency. The temperatures of arc are the higher the steeper the gradient $\frac{di}{dt}$ is at the moment of current zero crossing, because this results in less cooling time for the plasma. The ionisation of the plasma remains at a higher level, thus causing in higher probability of arc re-ignition [6, pp 28-31].

Altitude influences decisively the electrical breakdown of insulating distances and therefore is one of the major physical processes for interrupting fault currents. In a homogeneous electrical field, the breakdown voltage U_d between two electrodes depends on pressure and electrode gap and can be determined according to Paschen's Law (2).

$$Ud(p \cdot s) = \frac{b \cdot (p \cdot s)}{\ln[c \cdot (p \cdot s)]} \qquad (2)$$

$$c = \frac{a}{\ln(1 + \frac{1}{\gamma})}$$

with $b = 46\ V\ mm^{-1}\ hPa^{-1}$, $a = 1.75\ mm^{-1}\ hPa^{-1}$, $\gamma = 0.01$ ionization coefficient for air

Air has therefore a minimum breakdown voltage of 330 V which is reached at about p·s = 7 mm hPa. According to (3), this corresponds to an altitude of 33,5 km at an electrode gap of 1 mm.

For a real aircraft circuit breaker according to fig. 6a, the measurement with an AC voltage of 50 Hz results in a dependency according to figure 8. The used contact material was AgMo 35/65. Each point in the diagram represents the average value from 10 measurements.

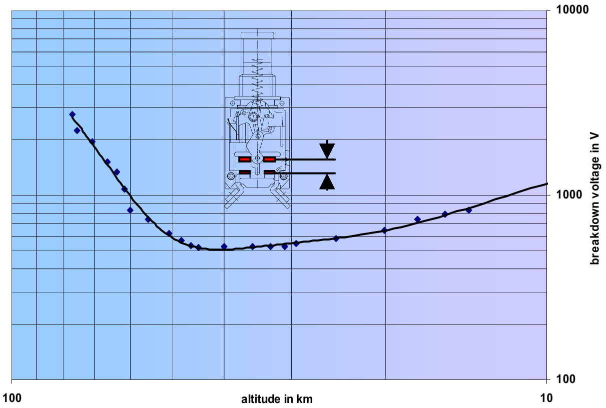


Figure 8 Breakdown voltage of a type 1 aircraft circuit breaker between open contacts as a function of altitude [1]

Here, the minimum breakdown voltage is approx. 500 V and is reached at pressure values corresponding to altitudes of 35 to 45 km. A high voltage test rig with 400 Hz was not available. According to [6], the breakdown voltage in nearly homogeneous fields rises by increasing frequency, because the polarity of the AC voltage changes before the (mostly positive) ions reached the counter-electrode during inception of the breakdown. This leads to a distortion of the electrical field and reduces the breakdown voltage. For frequencies below 1 kHz, this effect can be disregarded so that there can be assumed that the curve in figure 7 is also valid for an AC voltage of 400 Hz.

In order to test the behavior within higher altitudes, devices according to fig. 6a were switched at pressures corresponding to altitudes between 20 and 82 km. The switch current varied between 1 and 2 kA. The arc duration was determined by measuring the arc voltage on the test device (U_{arc} in fig. 5). Figure 9 shows the arc duration t_{arc} depending on altitude and switch current I, i.e. t_{arc} = f(h,i).

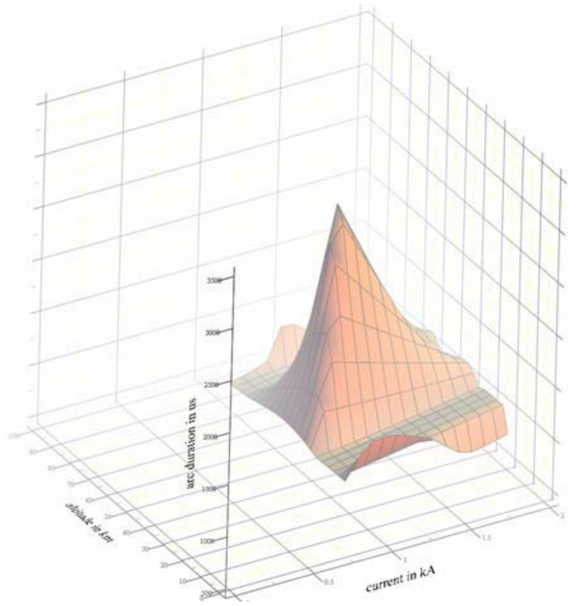


Figure 9 Arc duration t_{arc} [µs] as a function of altitude h [km] and current i [kA], circuit breaker type 1 [1]

Aircraft switching devices are usually licensed in military applications up to 30 km altitude. The area below 20 km was therefore not considered in the investigations. From an altitude of about 30 km, the arcing times rise extremely, reach a maximum at 50 km and at 60 to 70 km they fall off again to the original values. Towards higher currents, a distinctive maximum does not exist due to the higher contact dynamics. The peak value of the arc duration of 3 ms is at about 1,2 kA and 50 km altitude. On the basis of the decreasing breakdown voltage up to an altitude of approx. 40 km, it could be assumed that the dielectric recovery voltage also decreases at the same degree after extinction of the arc. Upon breaking the contacts we noticed that the arcing times lag behind the measured breakdown voltages of the Paschen's curve.

The length of arcing times decisively depends on the question if the dielectric recovery voltage of the positive space charge layer, which forms in front of the cathode after every current zero, increases faster than the transient recovery voltage above the contacts. According to [6, p. 30], the dielectric recovery voltage increases with following factors:

- lower cathode temperature, i.e. lower boiling temperature of the contact material
- higher work function from the electrode
- higher ionizing voltage of the electrode metal vapor
- lower column temperature by cooling effect

Obviously, the high work function of silver-molybdenum up to altitudes of 35 km is exceeding compared to the high boiling temperature and thus the relatively low instantaneous recovery voltage of the material [6, p. 28-31], [7, p. 101]. In altitudes between 35 and 65 km, the transient recovery voltage at 400 Hz and the opening speeds given by the circuit breaker's geometry increases faster than the dielectric recovery of the cathode layer. At currents higher than 1.5 kA, a sufficient instantaneous recovery voltage is reached again due to higher contact dynamics and a dielectric re-ignition of the arc is prevented. On even lower pressures from an altitude of 65 km, the mean free path of the particles exceeds the contact gap so that collisions and re-combinations do no longer occur and thus the breakdown strength rises again by that.

The re-increase of the arcing times at altitudes over 80 km to be observed in figure 9 can physically not be explained and may be caused by contact erosion due to repeated switching.

6. ARC FAULT PROTECTION

Aircraft wires have to survive in a very rough environment and therefore aging is accelerated compared to many other technical applications. As part of the insulation material for many aircraft cables polyimide (KAPTON®) had been used and still is used. In case of isolation faults, caused e.g. by vibrations, combined with pollution and humidity cable arc tracking may occur. If adjacent materials are ignited, the aircraft may crash in worst case. Therefore during the last 10 years arc fault circuit breakers (AFCB) had been developed by industry to avoid subsequent damage after occurring of arc faults. An AFCB does not avoid arc faults, but it prevents the arc from burning long enough to cause fire on board. Besides the normal circuit breaker functionality an AFCB contains additional sensors and electronics for signal evaluation to detect arc faults and to differentiate them from signals under normal load conditions. Low impedance arcs are generally less critical than high impedance arcs. For this reason arcs parallel to loads causing high current values are interrupted by the existing overload protection, but arcs in series to loads lower the current value and therefore cannot be detected by standard protection devices [5].

A typical oscillogram of supplying voltage, arcing voltage and current of a bank consisting of 10 fluorescent lamps shows *figure 10*. At this test a series arc was produced as it may e.g. occur, if there is a loose connection or a bad connector within the circuit. The arcing current is superimposed on the normal load current of the fluorescent lamps.

Signals like this appear in aircraft electrical systems under arcing conditions. That means, arc detection algorithms must safely detect a superimposed arc but on the other hand, must be highly resistant against these strongly non-sinusoidal waveforms produced by typical loads under normal rating conditions.

The arc voltage is not available, only the current signal can be recorded permanently. Special current sensors had been developed to allow an analog pre-evaluation in the high frequency range up to about 100 Mhz. Together with results obtained out of the low frequency current spectrum up to 50 kHz a criterion is calculated to decide, if there is an arc fault or a normal load condition. Meantime successful operating algorithms are available assuring not only arc fault detection at AC 400 Hz, but also avoiding nuisance tripping under all known load conditions.

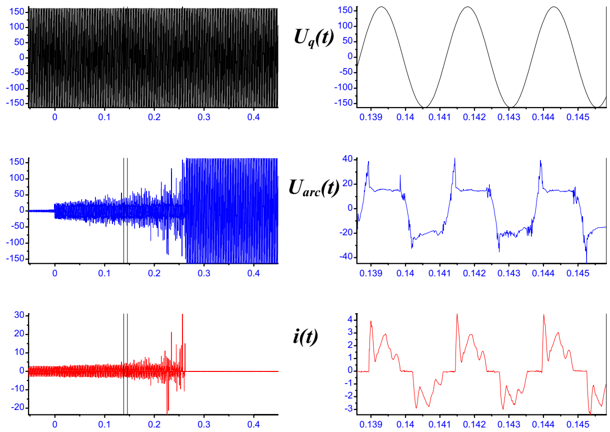


Figure 10 Fluorescent lamp with series arc, peak current about 4 A,. U_q supply voltage, U_{arc} arc voltage, i current [5]

DC currents need different detection strategies because the signals under arc fault condition show a very stochastic, intermittent behaviour and no more periodicity. *Figure 11* shows a current signal at DC 28V and a loose connection. The physical properties of the arc and statistical methods are used to detect faults under those circumstances [4] .

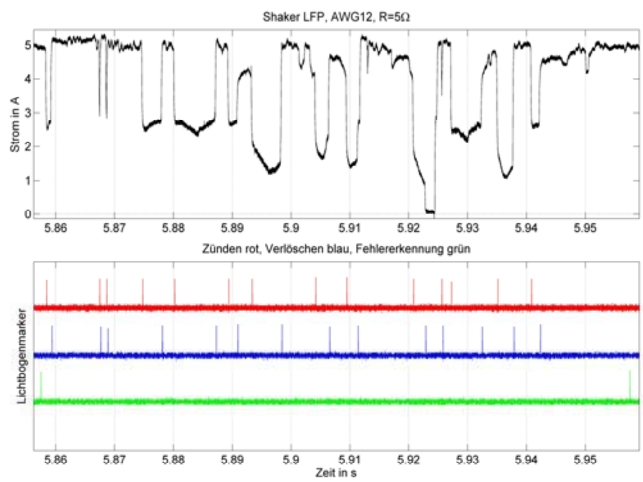


Figure 12 Typical DC current signal generated by a vibrating loose connection

7. CONCLUSIONS AND FUTURE PROSPECTS

The described investigations show the capability and the limits of existing mechanical aircraft circuit breakers at variable frequencies and flying altitudes.

Conventional aircraft circuit breakers can be used trouble-free up to altitudes of 30 to 35 km, being sufficient for civil and most of military applications. In altitudes between 35 and 65 km, it is possible that the switch device fails at currents between 1 and 2 kA due to reduced breakdown strength.

Existing mechanical aircraft circuit breakers are also appropriate for altitudes up to 22 km and frequencies up to 800 Hz and currents up to 2 kA. At 800 Hz and altitudes up to 22 km, no significant differences between AgMo and AgC/AgNi could be measured.

Future electronic solutions may not depend on pressure and frequency, but regarding size and power dissipation at alternative current they can still not compete with mechanical contacts regarding altitudes up to 30 km.

Electronic solutions are used for aerospace applications, because the risk to fail at start and landing is too high for existing electromechanical solutions due to the passing of the Paschen's curve.

Arc fault detection circuit breakers (AFCB) had been developed during the last 10 years and meantime are mature products ready to be built into aircraft power distribution systems. The protection technology, however, especially for lower current ratings also trends to be occupied by electronic solutions and therefore arc fault detection modules (AFDM) will be integrated in power control systems. This will increase safety and save weight and cost. Additionally time domain reflectometry (TDR) technologies will be used to detect fault locations after fault occurrence.

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